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J.D. LINDSAY

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J.D. Lindsay

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NEW DRYING AND DEWATERING PROCESSES IN PAPERMAKING

Jeffrey D. Lindsay
The Institute of Paper Science and Technology
Atlanta, Georgia 30318
USA

ABSTRACT

Current trends and advances in water removal technology for the paper industry are discussed. Most such innovations incorporate heat transfer mechanisms. Recent research results for two new water removal processes are presented. These new processes, impulse drying and displacement dewatering, have been proposed as possible means of saving energy while improving paper properties. While displacement dewatering has not yet lived up to its promise, impulse drying appears to have significant commercial potential. An improved understanding of phase-change heat transfer in paper is being sought to bring the impulse drying concept to fruition. Broad recommendations for future research are given.

INTRODUCTION

Water removal from a wet fibrous web is a critical operation in papermaking. Over 300,000 liters of water typically enter the paper machine for each ton of paper produced. Most of this water is removed by drainage and mechanical pressing. Only the final 0.5% or less of this water must be removed by evaporation, but doing so uses most of the energy needed for papermaking and requires a vast amount of equipment. There is definitely an economic incentive for improved water removal techniques. The motivation to adopt a new technology may not be strong, however, if only energy savings are offered. New (and thus potentially risky) water removal technology should also offer benefits in paper properties if it is to be accepted by the industry. Improved paper properties can mean new markets, or can allow a papermaker to meet specifications by using an alternative source of fibers.

In the critical areas of pressing and drying, a number of recent innovations have been developed which may result in energy savings or property improvements, or both. Many of these advances rely on some form of heat transfer. In this paper we will review a number of these advances, and will then focus on recent research involving two novel and related water removal strategies, impulse drying and displacement dewatering, for which energy savings and improvements in paper properties have been claimed. Phase-change heat transfer in impulse drying will receive special emphasis.

REVIEW OF ADVANCES IN MODERN DRYING AND DEWATERING

Innovations in Pressing Operations

Wet pressing is a time-honored process in which water is pressed out of a wet sheet by passing the sheet and an absorbent felt through a nip between two rolling cylinders. Since water not removed in the press section requires more expensive evaporative drying, efficient wet pressing is always desired.

In recent years, many purely mechanical advances have been made to improve water removal in wet pressing. Improved felt designs, double-felted nips, advanced roll covers, drilled rolls, grooved rolls, and innovative nip schemes are all examples. The development of the long or extended nip press (1) is one of the most important innovations, allowing a long, controlled pressure pulse to be applied to the wet sheet and a felt. Many of the most promising innovations, however, rely on heat transfer to improve or modify pressing operations. A number of these processes will be treated here.

Hot pressing. Hot pressing refers to a widespread practice of heating the web before it enters a press nip. Higher temperatures have several beneficial effects: reduced water viscosity means less resistance to water flow from the sheet to the felt; lower water surface tension means reduced rewet from capillary suction (bringing water from the felt back to sheet upon exiting the nip); and a softened fiber network means less resistance to compression (2).

Hot pressing today is achieved through steam showers before the nip of a press (3). Cross-directional control of steam delivery is now possible, allowing improved control over sheet moisture profiles. Sheet temperatures range from 60°C to 95°C. As a rule of thumb, a 10°C increase in sheet temperature tends to give a 1% increase in the solids content after pressing, which can mean about a 4% decrease in energy demand in the dryer section. Sheet properties are often enhanced, with various operations reporting improvements in moisture profiles and gains in either sheet bulk or density (not on the same machine, obviously). Higher machine speeds and the ability to use less expensive furnishes are also reported (4).

Efficient heat transfer with a steam shower is obtained by using steam near the saturation temperature, for superheated steam must first cool before it can deliver its heat of vaporization to the sheet. Heat transfer is also improved removing air in the condensing zone. This can be done in several ways, such as putting the steam shower close to the sheet surface, having a high-velocity steam curtain at the leading edge of the shower, or using a vacuum to remove the air (4).

The Tem-Sec press. The Tem-Sec or Direct Action Hot Press, a recent and now commercialized innovation, is a variation of wet pressing in which a large, heated, central roll acts as a common element for two or more press nips. Each nip is somewhat longer than conventional nips because of the size of the central roll (1.5-3.0 m in diameter). The central roll is internally heated with low-pressure steam, and each of the felts for the two nips may be heated, resulting in double-sided heating of the paper. Between the nips, the sheet is wrapped next to the hot central roll.

Like hot pressing, the Tem-Sec press enhances water removal by reducing water viscosity and by increasing the compressibility of the sheet (5). Good heat transfer is obtained by the two-sided heating and the close contact with the heated roll. Exiting dryness levels of 52-58% in linerboard have been reported. Slightly improved sheet strength is also claimed.

Impulse drying. Impulse drying is a novel water removal process which was proposed by Wahren (6) and subsequently developed at The Institute of Paper Science and Technology (IPST). At a superficial level, impulse drying can be described as a variation of wet pressing, with one roll heated to 250-375°C (see Figure 1). This is a much higher temperature than that used in Tem-Sec pressing or other existing thermally-assisted pressing processes. As a wet sheet passes through such a nip, intense heat transfer occurs, with peak fluxes ranging from

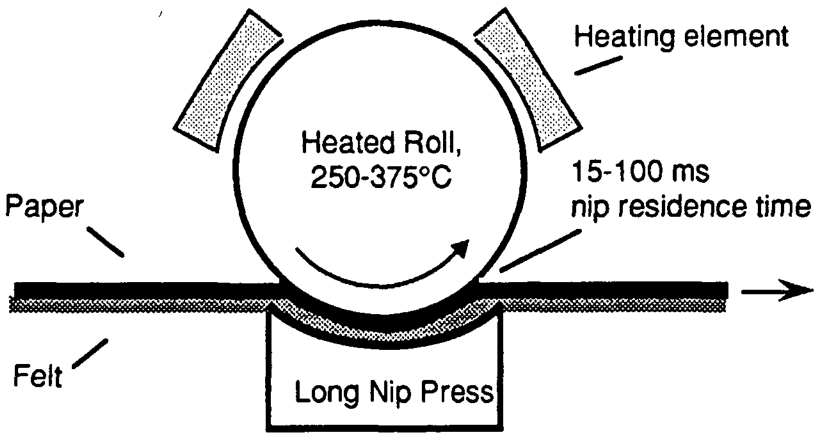

FIGURE 1. The impulse drying concept.

2 to 8 MW/m^2, rapidly tailing off to fluxes around 0.2-1.0 MW/m^2 during the 15 to 100 ms event. Through the interaction of heat transfer and other mechanisms, a large quantity of liquid water is expelled from the sheet; some water is also vaporized. The process has the potential to give higher dryness levels than wet pressing while using less energy than conventional cylinder drying (7).

Impulse drying not only offers the potential for energy and capital savings over traditional dewatering and drying methods, but can give significantly improved paper properties as well (7-9). The high surface temperatures in impulse drying enhance surface fiber conformability and interfiber bonding, resulting in increased tensile strength and surface smoothness. Researchers at The Pulp and Paper Research Institute of Canada (10) have examined impulse drying in newsprint, and have recently reported that in addition to the potential for substantial energy savings, impulse drying gives sheets with improved smoothness and higher breaking lengths and burst strength, although tear index and brightness may suffer slight losses. Strength improvement has been one of the major causes for industrial interest in impulse drying, as it would allow a required strength to be achieved with a lower weight sheet or with alternative raw materials (11).

A vapor-liquid displacement mechanism has been proposed as part of the physics of impulse drying. The high temperatures at the surface of the sheet correspond to vapor pressures which exceed the hydraulic pressures generated in much or all of a press nip. As a result, phase-change heat transfer will occur in the nip, leading to a pressurized vapor zone which can increase or sustain the hydraulic pressure gradient which drives liquid water out of the sheet into the felt. For example, Burton (8,9) conducted dynamic *in-situ* measurements of sheet density, vapor pressure, and temperature during simulated impulse drying. He concluded that a steam layer forming in the sheet helps to drive liquid water into the felt during impulse drying. A hot pressing effect also plays a role, as heat transfer warms the water and reduces its viscosity, making removal easier. Increased compression of the heated fiber webs will also contribute to water removal.

The commercialization of impulse drying has been delayed by the problem of delamination (12). In some fibrous webs, the vapor pressures generated can exceed the sheet strength as the sheet exits the nip, resulting in catastrophic sheet failure. The phenomenon of delamination must be understood and controlled before a commercial implementation of impulse drying is possible.

The physics of impulse drying have been the subject of some controversy recently, particularly in light of the troublesome delamination problem. Recent research results toward understanding impulse drying physics and the problem of delamination, with promising means for delamination reduction, will be discussed below.

Recent design improvements allow better mass transfer from the sheet by eliminating open draws of paper and the associated high humidity pockets (49). A number of other studies have shown significant improvements in performance are possible by modifying the gas flows associated with the dryer section (50-52).

NEW RESEARCH RELATED TO IMPULSE DRYING

Investigations of the Fundamental Physics of Impulse Drying

A number of recent studies at The Institute of Paper Science and Technology have sought to clarify the physics of impulse drying. A combination of both experimental and computational tools has been applied.

Flash x-ray visualization. In an effort to visualize the steam-water interface in impulse drying, Zavaglia and Lindsay (53) have used flash x-ray radiography to track the motion of x-ray-absorbing silver nitrate solution added to the upper layers of a linerboard sheet. Impulse drying and wet pressing events were simulated with a falling-weight press-nip device. During the pressing event, a 30-nanosecond burst of x-rays was sent horizontally through the sheet and the felt, passing then to x-ray sensitive film. The location of the silver nitrate solution in the z-direction could be observed in the radiograph.

Figure 2 shows a computer-enhanced radiograph taken of an impulse drying event. The light rectangle is the paper on top of a felt, bounded by metal surfaces above and below. Silver nitrate solution which was on the top of the sheet at the beginning of the event is now in the middle of the sheet, moving towards the felt. The radiograph was taken late in the event, during the sheet expansion phase. When the same experiment was done with a cool upper platen, the resulting wet pressing event did not remove the silver nitrate from the surface, but smeared it in the direction of the felt. The presence of a region virtually free of silver nitrate in the upper layers of the sheet implies that vapor has formed and displaced the liquid.

The peak mechanical pressure in this case was several times greater than what occurs in typical press nips, probably resulting in a more intense impulse drying process later in the nip. More recent radiographs (53) taken under more typical pressing conditions again show a low density region developing in the upper layers of the sheet in impulse drying, but the extent of the low density zone is not as great. It is believed that the observed low density region represents a dry zone; a larger two-phase zone containing both silver nitrate solution and steam may not be distinguishable from a saturated zone without further improvements in the experimental method. In any case, the existence of a vapor zone and the motion of fluid through a sheet can be observed with the flash x-ray technique.

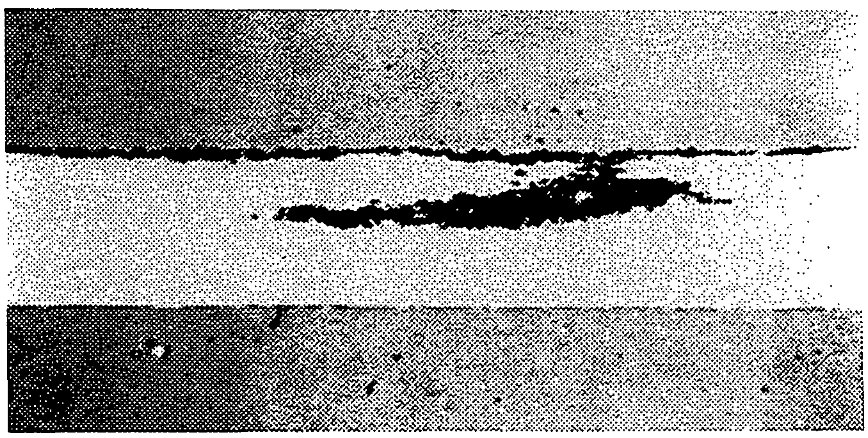

FIGURE 2. Computer-enhanced flash x-ray radiograph of an impulse drying event in linerboard on a felt. The dark region in the paper-felt zone is a drop of silver nitrate solution.

Displacement dewatering. Displacement dewatering denotes a process in which a pressurized gas phase is used to increase liquid water removal from a mechanically compressed sheet. Water is removed by both a pressing effect and a vapor-liquid displacement mechanism. This process is similar to what may occur in impulse drying, although in impulse drying the gas phase is generated internally by heat transfer. In the theory of displacement dewatering, high dryness levels may be achieved without the high densification required in pressing alone. The potential to decouple dryness and density has lead to recent investigations of displacement dewatering at IPST (13,14). The results of a recent study are summarized below.

If true displacement dewatering is achieved, relatively little vapor would be required to pass through the sheet – ideally only enough to uniformly displace the free water in the interconnected pores of a compressed sheet (1 MPa or more of applied pressure may be required). Unlike some other drying processes discussed below, the objective is to avoid significant vapor flow rather than drying the sheet by passing gas through. In practice, however, the gas in a displacement dewatering process is likely to break through some pores in the sheet and also remove water by entrainment and evaporation. This undesired effect is a common instability in gas-liquid displacement in porous media, and is known as "viscous fingering" (15).

Several approaches can be taken to reduce viscous fingering and thus improve the efficiency of a displacement process. Heat transfer in particular can play a role in decreasing instabilities (16). As a hot viscous finger penetrates into cooler liquid, the gas begins to cool and contract, thus decreasing the growth rate of the viscous finger. The most promising strategy, however, may be to use a condensible vapor as the displacing phase, as when steam displaces water. As fingers of steam penetrate into the sheet and contact cooler liquid, they will condense. The viscous fingers become self-sealing to a degree. The combined effects of heat transfer and condensation are believed to make superheated steam a good candidate for displacement dewatering.

Several technologies have been developed in the past which share some features with the displacement dewatering concept. Use of a gas phase to remove water by entrainment, as well as by evaporation, was patented by Holden in 1966 (17) and extended by Kawka and co-workers (18,19) over a number of years. In some devices, gas passes through a sheet that is under low mechanical pressure applied by porous belts, wires, or felts (20). Kawka's work focuses on blowing air through paper, especially absorbent papers and boards, and does not really deal with displacement. In general, the blow-through process, with light mechanical compression, is severely limited in the dryness that can be achieved in short times, and exposure times on the order of a second may be required (21).

A related concept of gas-liquid displacement in dewatering was addressed in a patent awarded to Gottwald, et al., in 1967 (22). Their proposed device was a heated drum at 120-250°C, wrapped with a wet web held in place by a porous belt under enough tension to cause at least 0.03 MPa (5 psi) of pressure on the web. They claim that vapor generated at the drum-web interface would drive liquid water into the porous belt, reducing the evaporative load on subsequent dryers. The proposed physics seem questionable, as a saturated liquid layer is not likely to exist under these conditions, but the possibility of *in-situ* steam-liquid displacement clearly was envisioned. This process can be viewed as a precursor to impulse drying.

Innovations in the Drying of Paper

Here we briefly review the current state of evaporative drying in paper, dealing with conventional cylinder drying after a discussion of several innovations from recent years.

Press drying. In the 1970s, Setterholm et al. (23,24) developed a method of drying paper while under mechanical compression which resulted in improved physical properties. The high strength developed in high yield furnishes was especially noteworthy. The heating and restraint times were large, measured in seconds rather than milliseconds. The apparatus for press drying typically includes two heated platens; wire screens may be added above or below the paper to provide a path for vapor escape. Platen temperatures from 150 to over 200°C have been used, with restraining pressures of 0.4 to 4 MPa. The drying method is purely evaporative; the effect of pressure is to increase the heat transfer and elevate the internal temperatures.

Several others have continued exploring the potential of this new process. Recent results again emphasis the high strength properties which develop, especially wet strength or water resistance, when pulps with high lignin content are used (25,26). The flow of polymeric materials, lignin and hemicellulose, at elevated temperatures accounts for much of the property improvement observed in this process (27). Hemicellulose flow improves bonding between fibers, and while the presence of lignin decreases dry strength, its interfiber flow at high temperatures can cover and protect previously formed bonds, leading to greatly improved water resistance in the paper (28). These mechanisms are probably similar to those that occur in the upper layers of a sheet during impulse drying.

The high residence times required for this process severely limit its application, but pilot machines have been developed which attempt to provide the necessary restraint over a long period of time (29). Press-drying is most effective when the incoming sheet dryness is between 50 and 70%, so some pre- and post-drying with a conventional dryer section may be required. In the future, press drying concepts may be especially fruitful in the drying of paper made from hardwood, where a naturally high lignin content leads to high strength.

<u>Thermal vacuum drying.</u> Lehtinen (30-32) has developed a novel evaporative drying method in which vaporized water from a sheet is removed by condensation on a cool surface. In the initial form of this process, a sheet is placed in a sealed enclosure in contact with a hot platen. Between the sheet and the chilled platen is a highly porous water receiver such as a felt or open matt. Air is removed by vacuum prior to the beginning of the process. Drying can occur at low temperatures due to the partial vacuum in the system, meaning that inexpensive waste heat can be used for drying. The vacuum also helps to compress the sheet and enhance conductive heat transfer from the hot platen. The process is said to yield drying rates much greater than in conventional cylinder drying. More recent forms of this process, better suited for commercial implementation, put the sheet between two continuous temperature-controlled belts. The ability to control temperature and the mechanical pressure on the belts offers increased control over paper properties. Low speed may impede commercialization.

<u>Through drying.</u> Through drying is a well developed technology in which heated air is passed through a highly porous sheet under minimal compression to evaporate water (33-36). Because the hot air contacts wet fibers across a large surface area inside the sheet, heat transfer is very efficient. A good discussion of the physics of this evaporative technique is given by Rohrer and Gardiner (37). Tissue and toweling are prime grades for through drying, although various filter grades, roofing felts, wiper grades, and many wet-laid nonwovens can be used (35). Both cylindrical and flat bed through dryers are made.

High velocity gas impingement in tandem with through drying has been investigated and patented by Burgess et al. at The Pulp and Paper Research Institute of Canada (38,39). In this "Papridryer" system, vacuum pressure inside a drilled suction roll pulls hot air through the sheet, decreasing boundary layer heat transfer resistance and causing internal heat transfer in the sheet. Randall (40) has investigated a similar concept using a honeycomb shell for the porous roll; the technique is aimed at grades with too much flow resistance for standard through-drying. It employs roll vacuum pressures up to about 0.012 MPa or 1.7 psi, and dwell times of 0.6 to 3.0 seconds. In the future, through drying will continue to be an important method for drying lightweight and highly porous grades.

<u>Improved impingement processes.</u> In addition to the Papridryer process mentioned above, impingement heat transfer plays several roles in the paper industry. The Yankee dryer for tissue grades represents a well developed impingement system where convective heat transfer is used to remove large amounts of water from highly porous tissue webs in a brief time. Impingement is also used in the drying of coatings, often in series with infrared heating. Flotation systems, with impinging streams of air supporting the sheet, are common (41).

One recent advance in impingement heat transfer with great potential for the paper industry will be noted here. Page and Seyed-Yagoobi (42) have developed a new impingement concept, Radial Jet Reattachment or RJR, in which the heated jet is deflected away from the heat transfer surface by a radial nozzle. The deflected jet reattaches to the surface, creating an intense recirculation zone inside the reattachment region. The intense turbulence and the disruption of the boundary layer result in substantially improved heat transfer rates. Perhaps even more importantly, the net force exerted on the surface can be positive, negative, or zero, depending on the angle of the deflected jet. Thus intense impingement heat transfer can be achieved without damaging the paper or without disrupting a wet coating. With negative forces possible, it should function well in a flotation dryer.

Dielectric heating. Radio frequency and microwave heating of paper has been explored as a means of paper drying. These forms of dielectric heating offer a great advantage over conventional drying methods in that the whole volume of the paper is heated rather than just the surface. Unlike conductive, convective, and typical radiative heating, drying is not dependent on surface heat transfer, and temperature and vapor pressure gradients do not dominate the process. The high costs of these techniques may limit their practical potential in the paper industry to profile correction, in which conventional drying is supplemented by occasional local dielectric heating to establish a uniform moisture profile in the cross-direction of a moving paper web. Given the importance of moisture profile control, however, dielectric heating is a technology which is likely to play an increasingly important role in the paper industry. The traditional way of achieving uniform moisture profiles has been to overdry the paper to 3 or 4% moisture, when drying to 5-10% moisture is all that is needed. Overdrying requires a reduction in machine speed and higher energy costs. Experience in Europe has indicated that higher machine speeds are possible with radio frequency drying for profile control, although accurate figures are not available (43).

Superheated steam drying. David et al. (44) have directly applied superheated steam to paper to cause evaporative drying. The authors suggest that energy savings may be possible because none of the latent heat of vaporization of water need be lost, since the outgoing steam can be used in subsequent processes. This technology is still in the developmental stage, but may offer some important benefits in sheet properties. Using steam at 350-450°C, strength improvements similar to those of press drying were found, without the loss in bulk that comes from pressing. In the absence of oxygen, cellulose degradation at high temperatures (a potential problem in air drying) was suppressed. Brightness properties were not reduced by the high temperatures. Superheated steam drying requires further development, but may prove to be of commercial importance in the future.

Developments in conventional cylinder drying. Evaporative drying of paper on hot cylinders is one of the most studied and best understood water removal processes in the paper industry. In spite of decades of experience with cylinder drying, recent advances often involve simple procedures which may improve performance and energy efficiency. For example, simply improving the testing diagnostics for dryer sections will help productivity and allow better heat transfer strategies to be implemented. Cross-directional measurements of dryer variables such as surface temperature and pocket humidity represent a potentially important advance in this area (45). Furthermore, while it is known that noncondensibles in a dryer will significantly reduce heat transfer and dryer efficiency, the industry-wide practice of using continuous bleeds to remove noncondensibles now appears to be an unnecessary and wasteful practice, especially if proper purging of the cylinders is done before start-up (46). Simply shutting off unneeded bleeds could thus result in large energy savings.

Several other modern trends, all fairly simple, can lead to improved performance. Operating at higher steam pressures is a general trend, but the marginal gains in heat transfer are limited. Controlling the condensed liquid layer inside the dryer is especially important. Most efficient operation occurs when the condensate forms a puddle at the bottom of the dryer, but at higher speeds rimming occurs, resulting in a continuous condensate layer inside the drum which impedes heat transfer (47). Solutions include the addition of "spoiler bars" in the dryer to break up the condensate layer, and improved siphoning techniques to minimize the volume of condensate (an example of a possible advance in siphon design can be found in [48]).

Evaporation in impulse drying. Measurements of water added to the felt by impulse drying and by wet pressing show that about 90% of the extra water removed by impulse drying in 250 g/m^2 wet sheets is in liquid form (the possibility of steam breaking through the sheet and condensing in the felt is easily ruled out by an examination of felt surface temperature in related measurements) (54). This is consistent with earlier energy balance and mass balance measurements made by Lavery (55,56). Enhanced *liquid* water removal is the key to potential energy savings in impulse drying.

Rewet reduction. An investigation of liquid water removal by impulse drying as a function of applied mechanical pressure provided indirect evidence that mechanisms other than displacement alone contribute to higher water removal (54). As a result, it was hypothesized that part of the enhanced water removal in impulse drying is due to the elimination of rewet (rewet is the transfer of water back into the sheet from the felt at the end of the nip by capillary or suction forces). With a pressurized vapor zone in the sheet, the normal process of rewet may be greatly reduced or reversed in impulse drying. This possible contribution to liquid water removal merits further investigation.

Temperature history. Measurement of local temperature histories within a sheet provides useful information. Burton (8,9) reported a measurement of internal sheet temperatures at three different layers inside a linerboard sheet during a simulated impulse drying event. In spite of uncertainties in the data, the temperature history in each layer is consistent with a displacement model of impulse drying, and could be interpreted as evidence that a distinct steam-liquid interface was moving through the sheet.

More extensive measurements of internal temperature propagation have recently been made at IPST (57, see also 54). Extremely fine thermocouples were sandwiched between thin, wet sheets of bleached kraft paper, each sheet having a basis weight of 50 g/m^2. During impulse drying with an MTS electrohydraulic press simulator, the temperature at each layer (including the felt-sheet interface) could be tracked in time. Sample results are given in Figure 3. Figure 3a shows the temperature at the felt-paper interface beneath a single 50 g/m^2 sheet. Three thermocouples at different locations on that interface were used, two of which gave similar results. Nonuniformities or a thermocouple problem may account for the third curve. The upper two curves show traits found in several of the measurements: a steep rise to a plateau above the ambient boiling temperature, followed by a rapid temperature rise which then levels off. Measurements at three transverse locations are shown in Figure 3b. Here three sheets have been stacked, and single thermocouples have been placed between the sheets. The upper curve from the thermocouple closest to the surface does not show an intermediate plateau. The second curve, showing data from the interface between the middle and bottom sheets, does show an S-shaped rise followed by a nearly flat region. The thermocouple at the sheet-felt interface shows only a gradual temperature rise.

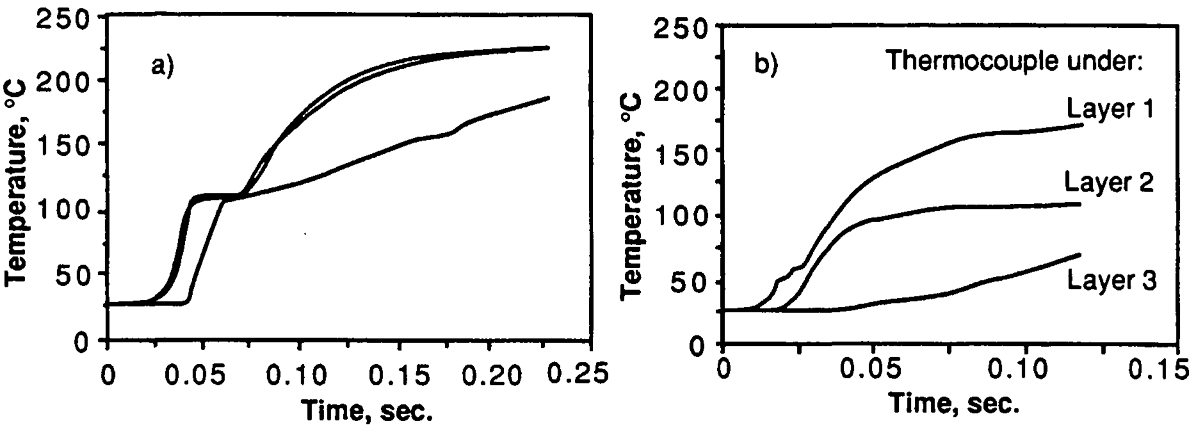

FIGURE 3. Temperature propagation in 50 g/m^2 sheets on a felt during impulse drying with a platen temperature of 260°C. a) Three simultaneous temperature measurements at different positions under one sheet on a felt. b) Temperatures between layers in a stack of 3 sheets.

A vapor-liquid displacement mechanism can account for the above results. The existence of plateau regions above 100°C is strong evidence for a two-phase zone where the vapor and liquid are in equilibrium at an elevated pressure. The two-phase zone at any point may only be temporary, and as it moves away, a dry zone with higher temperatures follows. In some cases, the two-phase zone is very thin (or nonexistent), so a sharp steam-water interface may be a good description of the process. Regions of slow temperature rise show the effect of transient conduction heating through a saturated liquid zone. In short, the data are consistent with the proposed displacement mechanism of impulse drying, and provide new evidence that extended two-phase zones may be formed during impulse drying. (The interpretation of these recent data has been aided by an examination of the numerical results from this study.)

Numerical modeling. In order to overcome the remaining roadblocks to industrial implementation of impulse drying, our physical understanding must be advanced. The difficulty of directly observing transport processes inside the nip, combined with uncertainties in interpreting experimental data, suggest that new tools are needed to supplement experimental studies. Numerical modeling is such a tool. While modeling cannot replace observation, the combined application of modeling and observation can lead to insights not available with either approach alone.

Recently, Lindsay (54) applied computational techniques to examine heat transfer in an idealized impulse drying process. The transient behavior of dry, two-phase and saturated zones in a one-dimensional, rigid porous medium was examined with a finite-difference moving-boundary model, MIPPS (Moving Interface Problems in Porous Systems). The problem included two internal moving boundaries each with changing temperature, pressure, and fluid velocity. Flow and heat transfer in the porous medium, including some capillary pressure effects, were accounted for. Temperature-dependent properties were used.

An early version of the model, MIPPS-I, attempted to simulate a heat-pipe mechanism of capillary wicking by using a wicking rate as an adjustable parameter (58). Only dry and saturated zones were allowed to exist, with wicking bringing fluid from the saturated zone back near the surface through a small subset of pores. A wicking rate of about 0.2-0.5 kg/m^2s then tended to give results consistent with measured data (primarily heat flux data). In MIPPS-II, the awkward wicking rate concept was eliminated, and a two-phase equilibrium zone was allowed to form (54,59). Specifically, bound or trapped water in pores remained immobile as vapor advanced until the liquid had been evaporated by heat transfer. The predictions of this presumably more correct model gave results similar to those of MIPPS-I. Sample results are shown in Figure 4. Predicted temperature profile results and the associated heat transfer mechanisms are qualitatively depicted in Figure 5.

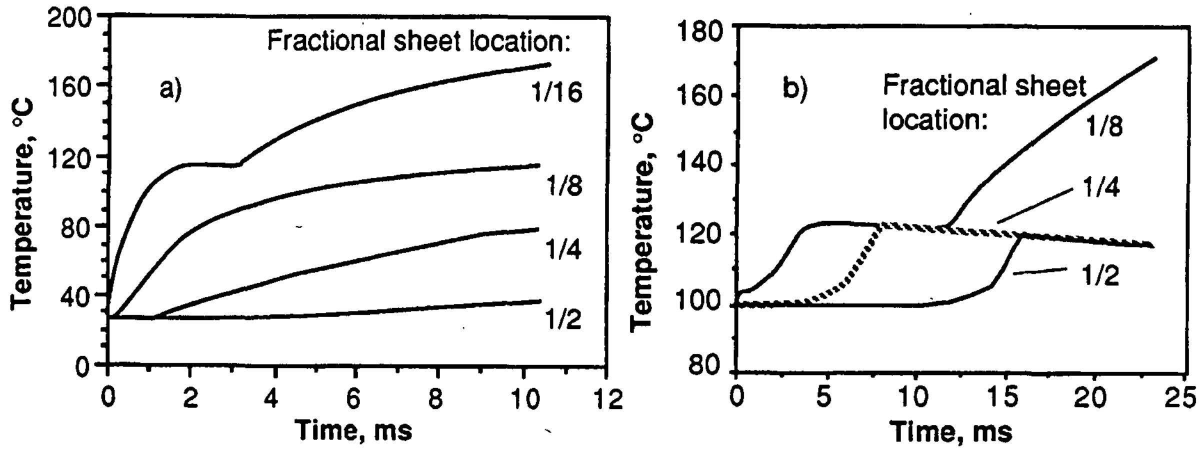

FIGURE 4. Two sample MIPPS-II predictions of local temperature histories in different paper sheets using different but realistic impulse drying conditions.

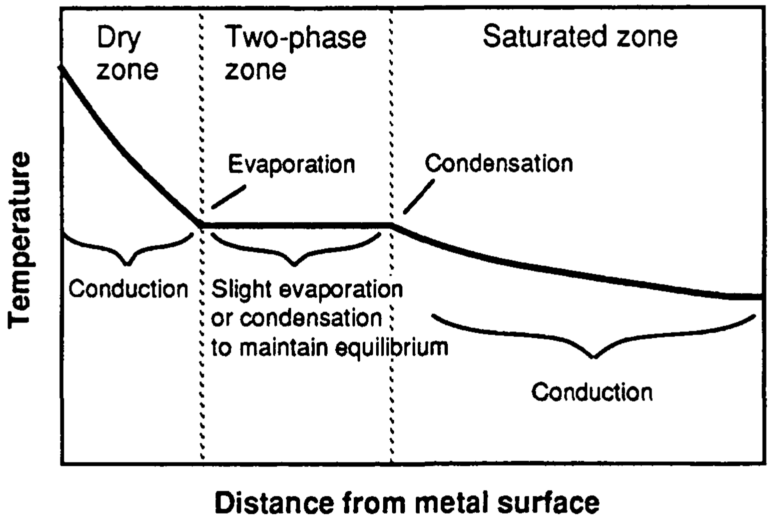

FIGURE 5. Temperature profile in a sheet and associated heat transfer processes during impulse drying (based on numerical predictions). Sketch is not drawn to scale.

Predicted local rates of evaporation and condensation have nearly equal magnitudes, giving a net evaporation rate in the nip close to zero. The process of evaporation and condensation is analogous to a heat pipe and gives heat fluxes beyond that of conduction alone. Simultaneous evaporation and condensation in the sheet is not an assumption but is a direct consequence of thermodynamics and conservation of energy.

Following recent modifications, MIPPS has been used as a design tool to choose materials and layer thicknesses in composite platen materials which provide some control over the heat flux delivered to the paper during impulse drying. The importance of controlling the thermal behavior of the hot surface is discussed below.

Boiling in fibrous media. In an attempt to overcome the lack of fundamental information about phase-change heat transfer in fibrous media (as opposed to the coarse granular materials for which boiling in porous media has been studied), Rudemiller and Lindsay (60) have studied boiling in thick ceramic fiber matts. Details of the experimental equipment are given in (61).

Boiling is modified by the presence of the fibrous bed, as illustrated in Figure 6 (only the nucleate regime of the pool boiling curve for water is presented). The boiling curve for the fibrous bed exhibits two boiling regimes and a point of transition between them. The first regime at low superheat is similar to nucleate pool boiling. The fibrous medium restricts bubble growth and detachment, making nucleate boiling less effective than in free liquid.

In the second regime, the heat flux is nearly constant, apparently controlled by the rate of liquid flow to the heater surface driven by capillary forces and gravity. A thin dry zone probably forms near the surface. An increase in superheat will cause the dry zone to grow until the conductive flux across that zone once again equals the flux required to evaporate water flowing down at a constant rate.

The point of transition between the two regimes is called the Transitional Heat Flux (THF). Interesting instabilities may be observed at this point, probably due to a redistribution of flow pathways for liquid and vapor. Macbeth has discussed some related phenomena in boiling in other types of porous media (62).

These steady-state experiments cover conditions far removed from impulse drying, which is a vastly more complicated process. However, the study represents a first step in characterizing phase-change processes in fibrous media. Further work is underway in this area.

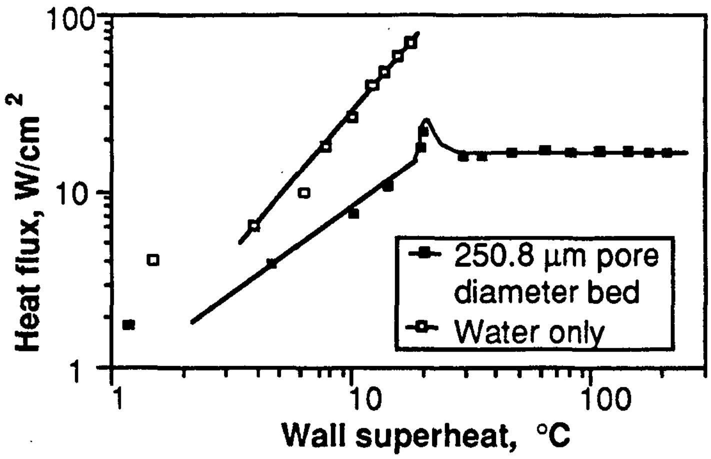

FIGURE 6. Typical measured boiling curves for pure water and water in a fibrous bed.

New Strategies for Delamination Control

As mentioned above, the problem of delamination has been the major stumbling block for the impulse drying process. In some furnishes, the internal vapor pressure is great enough to blow apart the sheet as it leaves the mechanical restraint of the nip. Wet sheets are more likely to delaminate than dry ones. Orloff (63) found that for a given sheet, delamination is a strong function of the operating conditions, especially nip residence time, platen temperature, and applied pressure. Conditions that improve water removal tend to increase the severity or likelihood of delamination. Burkhead et al. (64) also found that delamination was sensitive to felt moisture, with about 10-20% felt moisture giving better performance than either dry felts or wetter felts. They suggested that improvements in felt design might extend the operating window of delamination-free impulse drying. At that time, however, the prospects for delamination control looked bleak. Papermakers would not be satisfied with narrow operating windows for a new process. If it could not work well over a wide spectrum of conditions and for a variety of furnish types, the process would probably not be commercialized.

Important new advances in delamination control have now come from the extensive research of Orloff at IPST (65). Orloff has sought to control delamination by modifying the heat flux delivered to the sheet. His objective was to deliver a high heat flux early in the nip to generate the impulse drying effect, and then to significantly lower the heat flux near the end of the nip to reduce the internal vapor pressure. Simply lowering the temperature of a steel platen does prevent delamination, but also greatly reduces water removal. Initial work with porous platens did prevent delamination, but water removal was poor because steam vented into the platens, resulting in excessively low internal vapor pressures and preventing displacement. Orloff then developed novel composite platens with an external layer of impermeable, low-thermal diffusivity ceramic to modify the delivered heat flux. He found that the ceramic coated platens could give higher water removal in impulse drying without delamination than was possible with steel platens. (In one test series, for example, a moisture ratio change of 1.5 was possible without delamination using ceramic platens, while for the steel platens, delamination began at a moisture ratio change of about 1.1.) The use of ceramic coated rolls appears promising for effective impulse drying without delamination.

Current research in delamination control is concerned with optimizing the thermal properties of plasma-sprayed ceramic coated rolls by modifying the porosity of the ceramic. While measurements of surface heat flux in metal and ceramic coated platens have been made, experimental uncertainties have required improvements in the technique. These improvements are being achieved. Heat flux measurements will be combined with numerical predictions from MIPPS to guide design of future composite roll surfaces.

RECENT RESEARCH IN DISPLACEMENT DEWATERING

The displacement dewatering process has now been critically examined by Lindsay (14), following initially promising results from an earlier study by Sprague (13). The concept was tested with an electrohydraulic press, fitted with special heads that allowed gas (superheated steam or air) to be injected into a sheet while undergoing a mechanical pressing event. Finely drilled bronze plates acted as pressing platens, and the holes in the upper plate served as channels for gas flow. A wire or fabric mesh between the sheet and the upper platen distributed the load and the gas more uniformly. A felt was placed under the sheet. The concept was to apply pressurized gas during a pressing event to drive additional water into the felt, allowing high dryness to be achieved without the need to operate at high mechanical pressures which cause loss of bulk.

Dewatering, as expected, was limited by the permeability of the sheet, making long gas application times necessary. Lindsay examined displacement dewatering events ranging from 70 to 350 ms, with gas pressures up to 0.6 MPa (90 psi) and low applied mechanical pressures of 1.2-2.4 MPa (180-340 psi). For both superheated steam and cool air, displacement dewatering gave greatly improved dewatering compared to wet pressing under the same low-pressure press conditions. Steam was also much more effective than air, with solids levels up to 60% being possible in sheets initially around 20% solids, but much of the effect was due to evaporative drying after substantial heat transfer to the paper.

The most critical issue, bulk control, can be examined in several ways. In comparing densification in displacement dewatering to wet pressing run with the same low mechanical pressures and long nip times, displacement dewatering appears promising. The dryness-density curves show that displacement dewatering is superior in preserving bulk. However, when wet pressing is done under more conventional conditions (high-pressure, low-dwell time), the density-dryness results show that normal wet pressing usually gives less densification (higher bulk) than displacement dewatering. A set of data showing these features is presented in Figure 7. It appears that a creep effect occurs during long nip times, even at low mechanical pressure, and the resultant loss of springback leaves a denser sheet than expected. Steam displacement, while effective at water removal, densifies the sheet even more as it heats and softens fibers, lowering their compressive resistance.

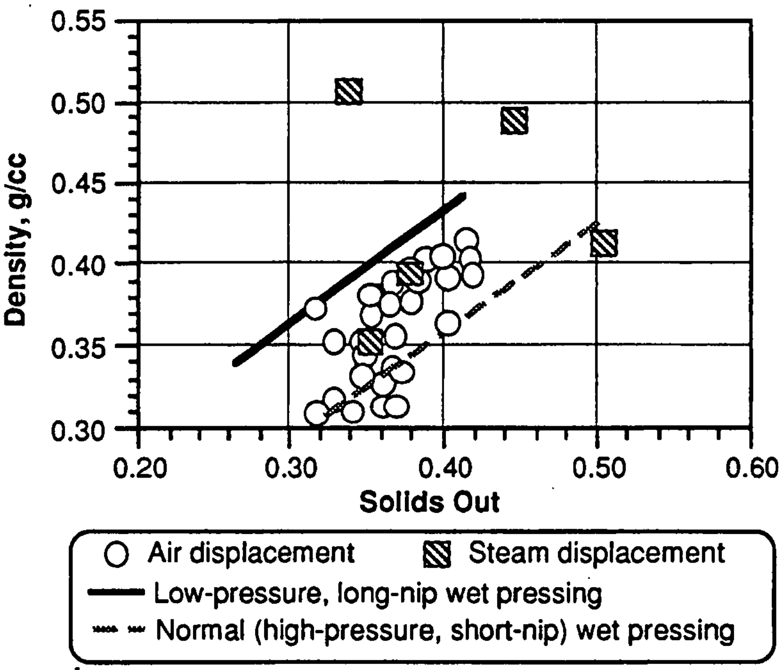

FIGURE 7. Density development in displacement dewatering of 100 and 150 gsm linerboard handsheets. Results from normal and low-pressure wet pressing are also shown.

The promise of improved bulk control thus has not been realized in the experiments done to date. However, it may be that a combination of higher vapor pressure and lower residence time may eliminate the apparent creep effect and maintain bulk in the sheet. The next stage of experimental work will seek to find operating conditions and pulp types where displacement is effective in preserving bulk and removing water.

FUTURE RESEARCH NEEDS

Many recent advances in water removal in paper incorporate heat transfer. Depending on the application, the benefits of heat transfer may include reduction of water viscosity or surface tension, sheet softening, induced flow of polymeric materials for better wet strength, improved fiber bonding, vapor generation to cause displacement, enhanced stability of a vapor-liquid displacement front, or simply vaporization of water. In every case, however, there is a need for more fundamental information about heat transfer in paper. Fundamental mechanisms are poorly understood, partially because of the complexity of paper and the difficulty of conducting measurements in a material that is both thin and heterogeneous.

Novel measurement techniques may open new doors in elucidating transport processes in paper. Flash x-ray visualization has proven helpful in studying impulse drying, and is now being applied to regular pressing operations to study in-plane shear (66). Infrared thermography is another visualization method which is advancing heat transfer research in paper (42). Numerous other measurement techniques may be or are becoming of use, including x-ray tomography, advanced microscopy methods, NMR and other forms of spectroscopy.

Numerical models of commercial pressing and drying processes were not reviewed in this paper, but represent a rich avenue for future progress. A major frustration to those developing such models, however, is the lack of data on transport parameters in paper (67). For example, a drying model may require information about the relationship between capillary pressure and saturation in paper, but this relationship may change significantly at elevated temperatures or under light mechanical constraint. The necessary data are unavailable, but could be measured. Even more basic thermodynamic properties, such as the heat of vaporization of water, change significantly when water is in the presence of small pores. Current research on the thermodynamics of vicinal water in cellulose (68) may prove of value here. A database of data on effective diffusion coefficients, contact resistance parameters, and other mass and heat transfer properties would be of great value to many researchers in addition to those developing models. Some progress is being made (69,70), but much more work is needed.

With regard to the research focused on in this paper, both impulse drying and displacement dewatering require further research in many areas. Plasma-sprayed ceramic coatings on rolls will soon be tested in a pilot impulse drying machine and may prove successful in controlling delamination, but more effective means may be discovered once the physics of impulse drying are more fully understood. Gamma radiation methods will soon be applied at IPST to study details of saturation profiles during boiling in a fibrous medium, and further studies are planned to give more insight into the complex phase-change heat transfer process that occurs in impulse drying. Bench-scale tests of displacement dewatering concepts need to be supported by more fundamental studies of vapor-liquid interaction in porous media. Since the issue of displacement stability is important to both impulse drying and displacement dewatering, studies in paper or a model fibrous medium may be helpful in guiding future thinking.

The importance of paper properties must be kept in mind as novel processes are developed. Heat transfer, already of value in enhancing some paper properties, may be useful in creating new new products rather than just new processes. For example, high-temperature processes like impulse drying may catalyze development of novel composite materials featuring paper and thermoplastics or thermosetting resins. Special high-lignin furnishes with polymer additives may be used to achieve new, inexpensive materials that compete with traditional plastics. Creative minds are needed to pursue the possibilities.

SUMMARY

Many recent innovations in water removal in paper involve heat transfer operations. Recent research results from two of these processes, impulse drying and displacement dewatering, have been presented. Impulse drying has received a considerable amount of attention and is approaching commercialization as new means for delamination control are being found. This unique application of intense phase-change heat transfer offers energy savings as well as property improvements. Displacement dewatering, a cousin of impulse drying, is still early in the developmental stage, and faces significant barriers in achieving the goal of good dewatering while maintaining bulk. With further research into the fundamentals of transport processes in paper, new advances in water removal and property development are expected.

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